A Discussion on the Origin of Groundwater Occurring Within the Coal Beds of the Powder River Basin, Wyoming

Wyoming State Geological Survey
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Introduction and Purpose

The question has been asked by some members of the public and other interested parties within the State of Wyoming:

> "***What is the origin of the groundwater occurring within the coal beds of the Powder River Basin?***"

This discussion has been prepared by the Geohydrology Section of the Wyoming State Geological Survey (WSGS) in response to this question and at the request of the Coalbed Methane (CBM) Water Task Force on June 5, 2006.

The simple answer to the question is that groundwater contained within a specific coal bed in the Powder River Basin (PRB) flows to a pumping well from the coal bed and all water-bearing geological formations connected to that coal bed. The more complex answer to the question is to discuss the origin of groundwater, all of the water-bearing geological formations potentially connected to the coal bed, and the movement of groundwater within the PRB. The complex answer also requires investigating:

- The potential sources of the groundwater;
- How water enters the coal bed and all formations connected to that coal bed; and
- How groundwater flows to a water well constructed into that specific coal bed.

The purpose of this discussion is to help answer the question from a geohydrological perspective.

Geological Structure of the PRB

The overall geological structure of the PRB is a plunging syncline with a basin axis located along the western portion of the basin. The large-scale geologic basin structure of the PRB is bounded on:

- The west by the eastern flanks of the Bighorn Mountains uplift;
- The southwest by the Casper arch;
- The south by the northern flanks of Laramie Mountains uplift including Casper Mountain;
- The southeast by the northwestern flanks of the Hartville uplift; and
- The east-northeast by the western flanks of the Black Hills uplift.

The oldest bedrock in the PRB is the Precambrian basement bedrock which is exposed in the cores of the mountain uplifts surrounding the PRB and underlies all younger formations in the structural basin. The sedimentary rock formations are exposed along the outer margins of the PRB and range in age from the Cambrian formations to the youngest bedrock formations (Wasatch and White River Formations) located in the central portion of the basin. The areally largest formation outcrop within the PRB is that of the Eocene age Wasatch Formation which present in large areas of eastern Sheridan County, eastern Johnson County, western Campbell County and north-central Converse County. The Wasatch Formation overlies all older bedrock formations in the PRB and the Wasatch Formation directly overlies the Paleocene age Fort Union Formation. The Fort Union Formation contains the major water-bearing coal beds of interest for the coalbed natural gas (CBNG) industry in the PRB.

Hydrologic Cycle

The overall movement of water on the earth is commonly known as the Hydrologic Cycle. The ultimate sources for all groundwater are the earth's atmospheres and oceans. Water daily evaporates from liquid surface waters and solid snow/ice areas and enters the atmosphere as water vapor. Atmospheric water is precipitated to the land surface in the form of rain, sleet, hail, and snow. Water sourced from precipitation may be evaporated again, runoff as surface water in streams and rivers, stored in ponds/lakes and reservoirs, or infiltrate downward into earth materials (soils, unconsolidated deposits, and bedrock formations) to become groundwater.

Geohydrology of the Powder River Basin

In arid to semiarid regions, such as the PRB of Wyoming, downward infiltration of snowmelt water, rainwater, and surface water are the primary sources of groundwater recharge. Locally, man-made recharge to groundwater from irrigation water, ponds/lakes, and reservoirs may provide a large source of recharge water to aquifers.

The potential sources for the origin of the groundwater contained within the Paleocene Fort Union Formation coal beds of the PRB may include one or more of the following:

- Connate water, which is the water entrapped within the geologic formations during original deposition of the sedimentary formations;
- Expulsion water, which is the water that was expelled from the accumulated sedimentary column in the PRB during the geologic processes of burial, compaction, and lithification. These geologic processes formed the sedimentary rocks and coal deposits from the unconsolidated sedimentary deposits;
- Diagenetic water, which is the water moving in or out of sediment/minerals/bedrock as an exchange medium during the chemical alteration of the minerals contained within the geologic formations;
- Meteoric water, which is the water that has fallen as precipitation from the atmosphere and has entered the geologic formations predominantly through outcrop, soils, and shallow subcrop areas;

- Surface water, which flows over permeable outcrops and subcrops of soils, unconsolidated deposits, and bedrock formations;
- Downward slow seepage of groundwater through low permeability beds of shale, claystone, mudstone, clayey siltstone, and clayey sandstone; and
- Structural water, which is subsurface groundwater flowing through geologic formations via fractures caused by structural deformation (folding and faulting of rocks) or cleat formation (fracture sets) within coal beds.

Regional groundwater in the PRB flows through permeable and water-saturated geologic formations/deposits. Regional flow occurs from the aquifer recharge areas, which are predominantly the bedrock formation outcrops located along the margins of the structural basin, towards the structural axis of the PRB, and down-gradient (downward in elevation) to the north-northwest into the Montana portion of the PRB. Regional groundwater flow is predominantly controlled by the structure of the PRB and the regional groundwater flow occurs in response to the force of gravity.

Locally, groundwater is under unconfined (water table) conditions in outcrops areas of the geologic bedrock formations along the margins of the PRB and in the shallow portions of the outcrop area of the formations. Groundwater flow is under confined conditions in the deeper areas of the PRB. Local groundwater flow, in areas where hills and uplands are topographically located above the local stream/river elevations, is dominated by these topographic features. Local groundwater tends to flow down-elevation into nearby surface drainages. Therefore, local groundwater flow may be in oblique directions or even the opposite direction to the regional groundwater flow direction. Local (site-specific) groundwater flow is predominantly controlled by the local topography adjacent to surface water drainages of the PRB and local groundwater flow also occurs in response to the force of gravity.

Complex surface water and groundwater interactions may occur between permeable soils, unconsolidated deposits, and bedrock and surface water drainages, which are typically lined with alluvial deposits. The infiltration of surface water downward or the discharge of groundwater upward into surface water drainages is dependent on the local hydraulic head pressure. In some reaches of streams, surface water infiltrates downward into the permeable zones recharging the local groundwater aquifers. Where this condition occurs, the stream segment is described as a “losing” stream. In other stream reaches, groundwater discharges upwards from local aquifers into the surface water drainage. Where this condition occurs, the stream segment is described as a “gaining” stream.

Using a summary of the published geometric mean values for hydraulic conductivity from pumping tests, the following estimated distances for groundwater flow in these formations over a 100-year period of time were calculated:

- Wasatch Formation about 1.4 miles;
- Fort Union Formation Wyodak coal bed about 5.5 miles;
- Fort Union Formation sandstone beds about 2.4 miles;
- Fort Union Formation coal beds about 6.2 miles; and

- Fort Union Formation siltstone and claystone beds about 0.05 miles.

From the above-listed data, we can see that the coal beds and sandstone beds have the highest mean permeabilities for groundwater flow and that groundwater in coal and sandstone beds generally moves the farthest distance during a given period of time within the PRB. Based on these data, groundwater may have required longer than 1,000 years to flow from the basin margins to the structural basin axis of the PRB (a distance of approximately 50 miles or farther).

Groundwater Flow within Coal Beds and Sandstone Beds

Although the coal beds in the PRB commonly contain some water (average 30% by weight moisture content in coals, an unknown quantity of which is likely connate water), the coal deposits have very low permeability for groundwater flow unless the coal beds have well-developed interconnecting cleat sets or other fractures present. Groundwater flow through a coal bed is generally via fracture flow. In permeable sandstone beds, groundwater flows through the interconnected pore space surrounding the sand grains and the mineral cements present between the sand grains in the sandstone. Groundwater flow within a sandstone bed is generally via porous flow and the Fort Union-Wasatch sandstone beds within the PRB typically have an estimated average porosity of 30 percent.

In areas of the PRB which have been sufficiently deformed by structures (folds/faults), fracture flow systems may have developed and vertically interconnect permeable water-bearing beds through adjacent low permeability interbeds. These fracture flow systems would allow upward or downward leakage of groundwater from one aquifer to another in response to the hydraulic head pressures of the groundwater present within the interconnected beds or formations.

During the time when a water well is pumping, groundwater from the surrounding water-bearing geologic formation(s) flows into the well through the open area (well screen, perforations, or open borehole) of the well. As pumping of the well continues, groundwater is drawn to the well from farther and farther away from the well. As groundwater is pumped out of the well, the water level in the well declines and the groundwater level in the surrounding water-bearing formation(s) is also lowered. The area of groundwater level decline caused by pumping a well is known as the area of depression, the cone of depression, or the radius (zone) of influence of a pumping well.

In a well field, pumping wells may be located close enough together to cause overlapping areas of depressions in the groundwater levels of a formation. During CBNG production, groundwater levels in an area are lowered by pumping water from wells and thereby causing a decline in the hydraulic head pressure of the groundwater in the coal beds. This pumping-caused decline in water pressure (hydrostatic/hydrodynamic pressure) within the coal bed, allows the natural gas under low pressure to flow into the CBNG wells from the coal beds and for the natural gas to be collected in piping at the ground surface.

Groundwater Quality

Groundwater present within the coal beds of the Fort Union Formation in the PRB is typically of the sodium bicarbonate-type and exhibits total dissolved solids (TDS) levels ranging from approximately 300 to 6,000 milligrams per liter (mg/L). Precipitation water (rain, sleet, hail, and snow) is relatively pure distilled-type water with very low TDS levels. As precipitation water comes in contact with earth materials (soils, sediment, and bedrock), soluble minerals (salts) are dissolved and carried in solution with the water during surface water flow or groundwater flow. Therefore, TDS levels tend to increase in the downstream direction of surface water flow and in the down-gradient direction of groundwater flow.

The lowest TDS levels observed in groundwater are generally present within the outcrop areas of the bedrock formations located along the basin margins of the PRB. The TDS levels in the groundwater commonly increase within each formation towards the basin axis of the PRB. The increasing TDS levels for groundwater aquifers from the basin margins to the basin axis also provide further evidence that the regional groundwater flow direction is structurally controlled and is towards the structural axis of the PRB.

Summary

The groundwater present in the coal beds of the Fort Union and Wasatch Formations in the PRB is likely to have been sourced from:

- Precipitation (meteoric) and surface water infiltration into outcrop areas of the permeable beds of these formations located along the margins of the basin, or in the case of the Wasatch Formation, infiltration into permeable beds exposed as surface outcrops within the central portion of the PRB. The groundwater migrates downwards in elevation and down structural dip in the PRB.
- Downward leakage of structural groundwater by gravity flow from overlying permeable water-bearing beds. The downward leakage would occur through fracture flow systems (fold/fault) completely penetrating the low permeability confining beds adjacent to the permeable water-bearing beds.
- Upward leakage of structural groundwater by higher hydraulic head pressure from underlying permeable water-bearing beds. The upward leakage would potentially occur through fracture flow systems (fold/fault) completely penetrating the low permeability confining beds adjacent to permeable beds.
- Small quantities of connate water remaining trapped within some of the sediments, minerals, and coal deposits in the PRB. The connate water is typically trapped within the less permeable beds of the formations and does not mix freely with other groundwater.
- Unknown quantities of either expulsion water or diagenetic water which may remain contained within the present-day geologic formations as groundwater.
- Some other unknown source of either groundwater or subsurface water flow, which may have provided groundwater to the coal bed aquifers.